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Abstract:

In this paper we present a novel approach for dynamic wavefront generation based on reconfigurable Opto-VLSI processing. Computer algorithms are developed to generate arbitrary quadric-phase lens and lenslet array with programmable focal length, beam steering and lens diameter by driving the Opto-VLSI processor with different computer generated phase holograms. Proof-of-concept experimental results show that multiple spheric and aspheric lens/lenslet wavefronts can be generated with each lens independently addressed. The measured maximum focal length tuning range is from ±80mm to infinity and the beam scanning angular range is ±7mrad, which are in excellent agreement with theory. Different spatial profiles for wavefront correction are also experimentally demonstrated.

1. Introduction:

An Adaptive Optics (AO) system is an optical system that employs real time wavefront sensing to detect and correct signal degradation caused by a non-ideal medium between an object and its image [1],[2]. In the past decades, AO has become a central technology in advanced optical imaging systems and attracted broad research interests in many application areas, such as astronomical telescopes, ocular wavefront aberration correction, satellite laser-guided missile systems, laser ophthalmoscopy, and advanced laser micro-fabrication systems. Figure 1 shows a typical AO system that rapidly senses the wavefront errors and dynamically generates wavefronts to correct the system final performance [3].

Several dynamic wavefront generation approaches have been demonstrated for different AO systems using deformable mirrors (DMs) as wavefront generation elements [4]-[7]. However, systems based on deformable mirrors are normally bulky, expensive and consume high power, and thus they are impractical especially when cost is a major factor in these systems. Opto-VLSI processors driven by digital multi-level phase hologram can perform adaptive beam steering, multicasting and focusing. These functions can efficiently be used for wavefront generation in different adaptive optics applications [8]. The advantages of Opto-VLSI processing include low cost, high reliability, compactness, easy control, low power consumption and high resolution.

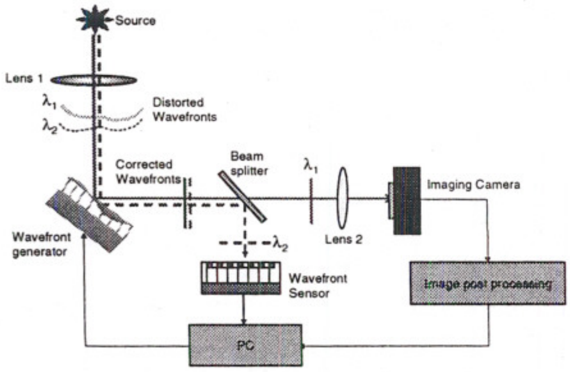


Fig. 1. Adaptive optical imaging system.

In this paper, we present a novel approach based on Opto-VLSI processing, which generates programmable quadric-phase lens/lenslet array. A diffractive model of phase-only diffractive element is used to calculate the evaluation of the modulation diffraction efficiency and pattern. Based on the diffraction analysis, an arbitrary quadric-phase lens hologram (QPLH) algorithm is developed to control the Opto-VLSI processor and realize dynamic wavefronts generation using MATLAB Software Package. By changing the input parameters of the QPLH, the Opto-VLSI processor can work as a dynamic Fresnel lens/lenslet or aspheric lens elements, such as a cylindrical lens array, thereby independently controlling the coordinates of the optical axes of each lens/lenslet element. Theoretical and experimental results show a 40-micron Opto-VLSI processor can realize tunable diffractive Fresnel lenses of focal length ranging from ±80mm to infinity and beam scanning angular range of ±7mrad.

2. Opto-VLSI Processor

A reconfigurable Opto-VLSI processor comprises an array of liquid crystal (LC) cells driven by a Very-Large-Scale-Integrated (VLSI) circuit that generates digital holographic diffraction gratings to steer and/or shape optical beams [9], as illustrated in Figure 2. Each pixel is assigned a few memory elements that store a digital value, and a multiplexer that selects one of the input voltages and applies it to the aluminium mirror plate. Opto-VLSI processors are electronically controlled, software-configured, polarization independent, cost effective because of the high-volume manufacturing capability of VLSI chips as well as the capability of controlling multiple fiber ports in one compact Opto-VLSI module and very reliable since beam steering/multicasting is achieved with no mechanically moving parts. Figure 2 also shows a typical layout and a cell design of an 8-phase Opto-VLSI processor. Indium-Tin Oxide (ITO) is used as the transparent electrode, and evaporated aluminum is used as the reflective electrode. The ITO layer is generally grounded and a voltage is applied at the reflective electrode by the VLSI circuit below the LC layer. A quarter-wave plate (QWP) is also inserted between the aluminum mirror and the LC layer making the Opto-VLSI insensitive to the polarization of the input optical beam [10].

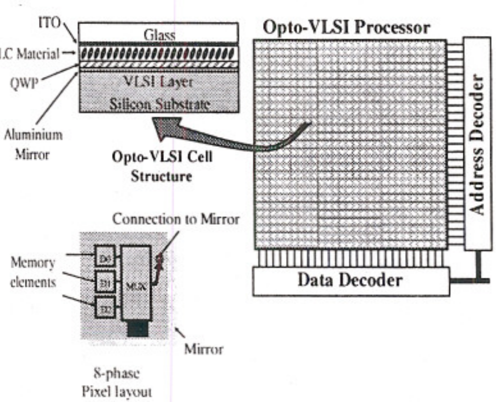


Figure 2. Opto-VLSI processor layout.

3. Diffraction model and algorithm

The Opto-VLSI processor can be analysed as a phase-only diffractive optical element with a maximum phase of 2π. To calculate the diffraction efficiency and diffractive pattern of the phase hologram generated by the Opto-VLSI processor, we employ the diffraction model presented in [11] which evaluates the diffraction pattern when an ideal phase-only diffractive optical element is used to produce wavefront generation with perfect phase modulation. If $h(x,y)=\exp[i\phi(x,y)]$ is the phase-only function generated by the Opto-VLSI processor, then the corresponding diffraction pattern is generally expressed by a complex modulation function given by:

$$g(u,v)=\int_{x=-\infty}^{\infty}\int_{y=-\infty}^{\infty} h(x,y)\exp\left[\frac{i(x\cdot u+y\cdot v)}{\lambda f}\right]dxdy \qquad (1)$$

For a quadric-phase lens, the phase function $\phi(x,y)$ is given by

$$\phi(x,y)=-2\pi \bmod\left(\frac{n\cdot(x+x_0)^2+m\cdot(y+y_0)^2}{\lambda f}\right) \qquad (2)$$

where λ is the optical wavelength, f is the focal length of the designed Fresnel lens. The parameters n and m determine the lens phase distribution. x_0 and y_0 represent the coordinates of the optical axis of the lens synthesized by the Opto-VLSI processor. The modulo function ensures that the phase remains between 0 and 2π. Note that, in Eqs (1) and (2) the coordinates (x, y) have to be kept below their maximum values (x_{max}, y_{max}) which represent the size of the pixel block used to synthesized the lens. Since the Opto-VLSI processor has a limited number of phase levels within the range of 0 and 2π, only phases that are rounded to the nearest available discrete levels can drive the hologram. From equation (2), we can design the following special wavefronts:

On-axis Fresnel lens: When $n = m = 1$ and $x_0 = y_0 = 0$, the phase function $\phi(x,y)$ will be an ideal Fresnel lens with an on-axis focus, and its focal length f can be calculated from the following equation:

$$\phi(x,y)=\pi(x^2+y^2)/(\lambda f) \qquad (3)$$

If $\phi(x,y)=2\pi$, maximum focal power is achieved and the minimum focal length is given by:

$$f_m=(x_{\max}^{\ 2}+y_{\max}^{\ 2})/(2\lambda) \qquad (4)$$

Off-axis Fresnel lens: When $n = m = 1$ and $x_0 \neq 0$ or $y_0 \neq 0$, the phase function $\phi(x,y)$ will be Fresnel lens with an off-axis focus, its function is equivalent to a ideal Fresnel focusing lens plus a prism to steer the focused beam from the reference axis. Its maximum focal power is also calculated using equation (4), and the maximum steering angle is given by:

$$\theta_m=\frac{2\lambda}{(x_{\max}^2+y_{\max}^2)^{1/2}} \qquad (5)$$

Cylindric lens: When $n = 0$ or $m = 0$, the designed phase function $\phi(x,y)$ will generate diffractive pattern as a cylindrical lens. Its focal length can be calculated as:

$$\phi(x)=\pi\cdot x^2/(\lambda f)\quad (m=0) \qquad (6)$$

Or $$\phi(y)=\pi\cdot y^2/(\lambda f)\quad (n=0) \qquad (7)$$

The maximum focal power and steering angle can also be calculated using equation (4) and (5), with x_{max} or y_{max} are set to zero, depending on whether the cylindrical lens is oriented along the y-axis or the x-axis, respectively.

Lens array: When the active area of the Opto-VLSI processor is subdivided into different sections with each section driven by an independent hologram, a dynamic diffractive lens array is synthesised, where each lens can have a different diameter to perform beam focusing, steering, multicasting, and shaping. Equations (4) to (7) can be used to calculate the focal length of each lens element and the corresponding steering angle, by appropriately selecting the parameters n, m, x_0, y_0, x_{max}, and y_{max}.

Using equations (4) to (7) enables us to theoretically evaluate the performance of the Opto-VLSI processor and predict its output capability to synthesize dynamic lens array of variable focal length and steering angle. For example, when a $5x5mm^2$ active area of the Opto-VLSI processor is driven by a Fresnel lens with peak phase of 2π, x_{max} = 2.5mm, y_{max} = 2.5mm, and for λ =1.55μm, the calculated minimum focal length is $f_M \approx$ 4.5m and the maximum steering angle is $\theta_M \approx$ 0.88mrad. However, driving the OPto-VLSI processor with an 8×8 lens array, where each element has a maximum phase of 2π , i.e. x_{max} = 0.32mm, y_{max} = 0.32mm, then the calculated minimum focal length is $f_M \approx$ 65mm and the maximum steering angle is $\theta_M \approx$ 7mrad..

4. Experimental setup

Throughout the experiments, the Opto-VLSI processor used was a 1550nm 128-phase 128×128-pixel nematic liquid crystal device with 40-micron pitch size and 60% fill factor. MATLAB Software Package was used to generate different lens and lenslet wavefront holograms based on equation (2), and then the programmed holograms were loaded to drive the Opto-VLSI processor. Figure 3 shows the experimental setup that demonstrates the concept of dynamic lens and lenslet wavefront generation using the Opto-VLSI processor. A 1550nm signal laser light generated from a tunable laser source (Agilent 86410B) was launched into an input fibre collimator which generated an output beam of 1mm diameter. This beam was expanded to 5 mm by a beam expander so that it filled most of the Opto-VLSI processor working area. The diffracted output laser beams from the Opto-VLSI processor were imaged by an imaging lens and captured by a CCD camera, and the captured beam profiles were analysed using the beam profile analyser Spiricon.

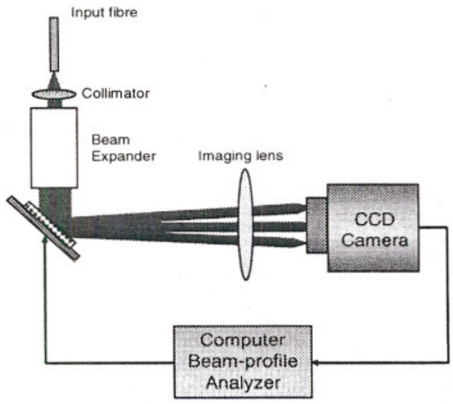
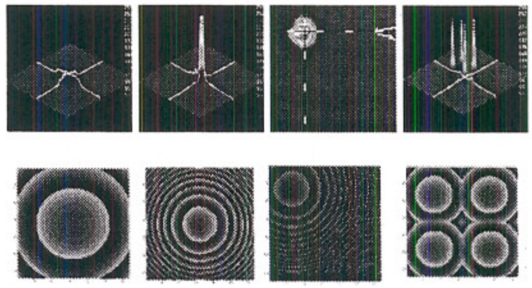


Fig. 3 Experimental setup for dynamic Lens and lenslet wave-front generation.

5. Experimental results:

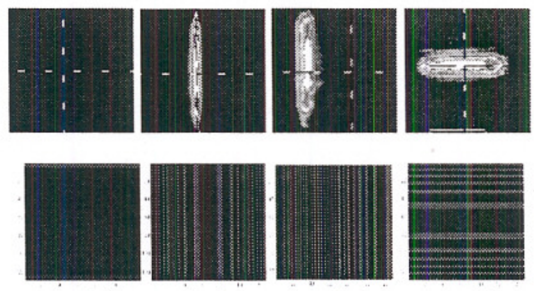
Figure 4 show the measured output beam profiles and corresponding Fresnel lens holograms for different focal lengths and beam steering. Figures 4 (a) and (b) demonstrate the capability of the Opto-VLSI processor to dynamically focusing the input beam by varying the focal length of the synthesized Fresnel lens hologram. It is important to notice that the measured 3-D output beam profiles are fairly Gaussian. In Figure 4(c), the centre of the Fresnel lens was shifted so that beam steering is added to the focusing capability of the Opto-VLSI processor. The 3-D output beam profile shows that the shift of the Fresnel lens centre is equivalent to the superposition of a Fresnel lens and a steering prism. In Figure 4(d) the generation of a 2×2 Fresnel lens array is demonstrated.



(a) (b) (c) (d)

Fig.4 Measured output beam profiles and corresponding Fresnel lens holograms. (a)-(b) output beam size varies by changing the focal length. (c) beam steering added to beam focusing (d) 2×2 lens array generation.

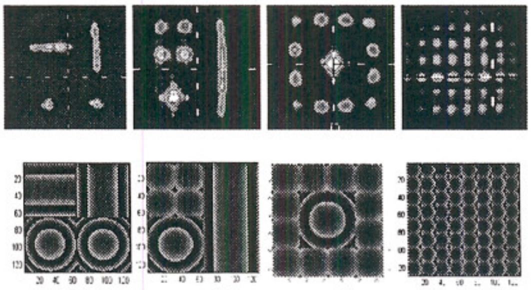
Figure 5 show measured output beam profiles corresponding to cylindrical lens holograms with different focal axis and beam steering. Figure 5(a) corresponds to a blank hologram. Figures 5 (b) and (c) show the capability of the Opto-VLSI processor to focus the input opticl beam along the x-axis by uploading cylindrical lens holograms synthesised using equation (9). Beam focusing as well as steering are shown in Figure 5 (c). Similarly, Figure 4(d) demonstrates the capability of the Opto-VLSI processor to focus the input beam along the y-axis. It is noticeable that the output beam profile is Gaussian along both the x-axis and the y-axis.



(a) (b (c) (d)

Fig.5 Measured output beam profiles and corresponding Cylindrical Fresnel lens holograms.

Figure 6 illustrates the capability of the Opto-VLSI processor to synthesize adaptive lens arrays of arbitrary beam shaping using Fresnel and cylindrical lenses. These profiles were generated by partitioning the Opto-VLSI processor to an array of discrete pixel blocks each driven by a Fresnel lens hologram of different characteristics. These experimental results clearly show that the dimension, centre and phase distribution for each lens element can independently be adjusted, making the Opto-VLSI processor an efficient wavefront generator for AO systems.



(a) (b) (c) (d)

Fig. 6 Adaptive lens arrays generation using Opto-VLSI processor: Captured output beams and corresponding lenslet holograms.

The measured focal length dynamic range was from 80 mm to infinity and the maximum steering angle was about ±7mrad using 8×8 array phase holograms, the results are in excellent agreement with theory.

6. Conclusions:

The use of a reconfigurable Opto-VLSI processor for adaptive optical wavefront generation has been presented and its feasibility for generating arbitrary spherical and aspherical wavefront has been demonstrated. Phase-only diffraction analyses were used to theoretically calculate the focal length and beam steering angle of Opto-VLSI processors. Based on the theoretical analysis, MATLAB Software has been used to generate dynamic quadric-phase lens/lenslet array holograms that drive the Opto-VLSI processor. Proof-of-concept experimental results have demonstrated different wavefront generations, including Fresnel and cylindrical lens/lenslet arrays featuring programmable focal lengths and beam steering angles. Theoretical and experimental results have also demonstrated a focal length dynamic range from ±80mm to infinity, and a maximum beam steering range of ±7mrad, and invariably Gaussian output beam profiles. Opto-VLSI processors have applications in dynamic wavefront generation for adaptive optics systems.

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